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# Impact Of Climate Change On Human And Ecological Use Of Karst Groundwater Resources: A Case Study From The Southwestern USA

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# IMPACT OF CLIMATE CHANGE ON HUMAN AND ECOLOGICAL USE OF KARST GROUNDWATER RESOURCES: A CASE STUDY FROM THE SOUTHWESTERN USA

**_George Veni_**
*National Cave and Karst Research Institute*
*400-1 Cascades Avenue*
*Carlsbad, New Mexico 88220, USA*
*gveni@nckri.org*

## Abstract

Climate change models for the arid southwestern USA predict increasing temperatures and declines in precipitation. These changes will have multiple adverse impacts on water and ecological resources and pose diverse challenges on their management. The San Solomon Spring system of west Texas discharges from the western edge of the karstic Edward-Trinity Plateau Aquifer. It consists of six springs in Jeff Davis and Reeves counties, is one of the largest spring groups in the state, and provides water for agricultural use and habitat to two federally listed endangered species and three species proposed for listing. It serves in this paper as a case study for the impact and management of climate change on springs in the American southwest.

Water and ecosystem management can be driven by market and/or ecological forces. Market considerations can guide water management if there are no ecological or other considerations that depend on aquifer levels or flowing surface water, and if total water use is sustainable for the climatic conditions. Where endangered species are involved, ecological factors dominate management, but require greater levels of information and understanding of the relationship between aquifer conditions and ecological health. Computer software, such as ADAPT, are starting to become available to assist with local climate change evaluations and decision-making processes.

## Introduction

Climate change is frequently in the news. It has become a common topic of discussion and debate as to whether changes in the weather, major storms, and small rises in sea level are the result of changes in global climate. While reports of new record high temperatures and graphs showing near-exponential increases in atmospheric carbon dioxide become more familiar, the direct impact on people's daily lives and the ecosystems surrounding us remain somewhat abstract. Computer models continually improve and provide better estimates of global shifts in climate and weather patterns. Studies of their impacts at the local level are starting to emerge. This is such a study.

Friedman (2008) aptly described climate change as "global weirding," as opposed to the more familiar "global warming." While average global temperature is increasing, the changes are not uniform between regions or always intuitive. Consequently, a paper of this scope cannot address the impacts of climate change on karst groundwater resources globally or even across the United States. Instead, this paper examines a region in west Texas as potentially representative of karst groundwater needs by humans and endangered species in the arid American southwest. It begins with a review of one karst spring system, then compares it to another nearby to examine different response models for predicted groundwater availability.

## Site Description

The San Solomon Spring system is located at the western edge of the Edwards Plateau in Jeff Davis and Reeves counties, Texas. The springs occur in and near the City of Balmorhea (population approximately 500) and the community of Toyahvale and Balmorhea State Park (Figure 1). San Solomon Spring is the largest of six springs (East Sandia Spring, Giffin Spring, Phantom Lake Spring Cave, San Solomon Spring, Saragosa Spring, and West Sandia Spring) distributed over a 13-km long by 2-km wide northeast-southwest trending area, and is the featured attraction of Balmorhea State Park.

The springs were used by Native Americans since prehistoric time. Their irrigation canals were visible as late as 1898 (Hutson, 1898). In 1583 Spanish explorer Antonio de Espejo made the first documented discovery of San Solomon Spring (Castaneda, 1936), and possibly the other springs, although modern settlement of the area

didn't begin until the mid-1800s with the establishment of Balmorhea (Miller and Nored, 1993). Modern irrigation canals carrying flow from the springs were dug as early as 1853 (Brune, 1975).

From 1961-1990, the San Solomon area had a mean annual maximum temperature of 23.9 ºC and average annual precipitation of 30.8 cm (Anaya and Jones, 2009). The springs are situated at an average elevation of 1,000 m above mean sea level. The area consists predominantly of nearly horizontal Quaternary alluvial plains that slope and drain to the east. Limestone hills skirt the western edge of the area at Phantom Lake Spring Cave, and small Tertiary igneous hills associated with the Davis Mountains delimit its southern and eastern margins. Most of the area is rural pasture and farm land.

The San Solomon Spring system is often described as discharging from the Edwards-Trinity Aquifer, which is comprised of Lower Cretaceous age carbonates of the Washita and Fredericksburg groups, and the carbonates and clastics of the underlying Trinity group. However, at this western edge of the aquifer the Buda Limestone is mapped by Barnes (1982) as separate from the Washita (the Buda is generally considered a part of the Washita Group) but is it recognized as hydrologically continuous with and a part of the Edwards-Trinity.

Phantom Lake Spring Cave discharges from the Buda Limestone, which north and east of the cave dips and is down-faulted under the alluvial plain. Well data from White et al. (1938) show the limestone extends below the other San Solomon system springs which flow from the overlying alluvium. Although that early report suggests the source of Saragosa, East Sandia, and West Sandia springs was the local alluvial aquifer (the southwest edge of the Cenozoic Pecos Alluvium Aquifer), Chowdhury et al. (2004) demonstrated geochemically that East Sandia flows from the Edwards-Trinity (their study did not include Saragosa and West Sandia springs).

In January 2013, Veni and Land (in prep.) injected uranine dye into the downgradient section of Phantom Lake Spring Cave, which does not discharge from the cave's entrance. The dye arrived at San Solomon Spring six days later, having traveled at a minimum average rate of 1 km/day. Dye was not detected at any of the other springs or at any of four monitored wells. Their results suggest little inflow from other sources into the cave stream between the dye injection point and San Solomon Spring.

LaFave (1987) and LaFave and Sharp (1987) determined the cave and San Solomon Spring were fed by two sources of waters. Using hydrograph and geochemical evidence, they identified a local source of recharge in the Cretaceous limestones immediately west of the springs. These data also identified the Permian carbonates of the Apache Mountains, 40-80 km northwest of the cave, as a more distant recharge area that sustains much of the springs' baseflow. Their results were confirmed through more extensive geochemical analyses by Uliana (2000) and Chowdhury et al. (2004). Figure 1 shows the recharge area for the springs as roughly estimated by Veni and Land (in prep.). Sharp (2001) provided potentiometric and geochemical evidence which indicates that much of the groundwater flowing through the Apache Mountains is fed by an extensive system of alluvial bolson aquifers on the west side of the mountains; this potential recharge area is not considered in Figure 1.

Groundwater in the Apache Mountains is hypothesized to flow into the Cretaceous limestones where they are juxtaposed with the Permian units in the subsurface by the Stocks Fault near the mountains' east end. From there, the groundwater flows southeast along the fault, and then past the fault further southeast down the Rounsaville Syncline, until it is seen at Phantom Lake Spring Cave followed by the other San Solomon springs (LaFave, 1987; LaFave and Sharp, 1987). Upstream exploration of the cave by divers supports this hypothesis, having extended the survey of the cave 1.4 km northwest of the entrance along the east flank of the syncline. The cave has a total surveyed length of 3,075 m and is the deepest underwater cave in the US with a depth of 140.8 m at the current limit of exploration (ADM Exploration Foundation, 2013).

## Local Water Resource and Ecological Challenges

In 1986, the Texas Water Commission proposed the locale of the San Solomon Spring system as part of a "critical area" that "is experiencing or is expected to have ground-water problems resulting from ground-water overdrafts from an aquifer" (Ground Water Protection Unit, 1989). Ashworth et al. (1997) cursorily examined the declines in San Solomon system spring flows and concluded they resulted from decreased rainfall since

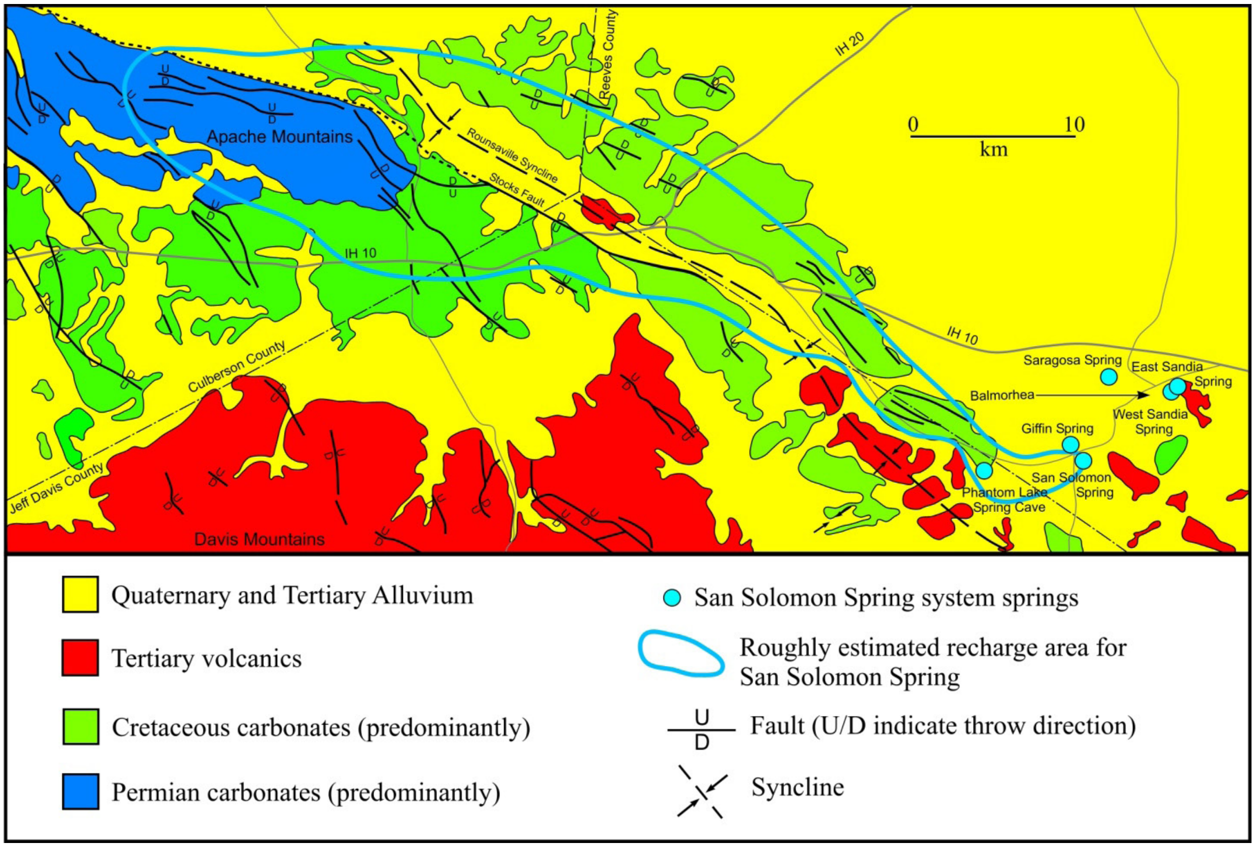


***Figure 1.*** *Simplified hydrogeologic map of the San Solomon Spring system region (based on Barnes, 1975, 1976, 1979, 1982; LaFave and Sharp, 1987). Balmorhea State Park surrounds at San Solomon Spring and Toyahvale is next to Giffin Spring.*

1992 to the date of their study. However, Brune (1981) showed that the drought of record in the 1950s had no measurable effect on flow from Phantom Lake Spring Cave, the second largest and most upgradient spring. Further, Brune (1981) documented generally sustained declines in flow from East Sandia Spring, Phantom Lake Spring Cave, San Solomon Spring, and Saragosa Spring since 1945, when irrigation pumping began to greatly increase and major declines in water levels occurred in the adjacent Cenozoic Pecos Alluvium Aquifer (Texas Water Development Board, 1986; Sharp, 2001). The potential impact of significant groundwater declines in the Cenozoic Pecos Alluvium Aquifer on the springs' flows has not been studied.

Whatever the cause, the effect of diminished spring flows has been most noticed at Phantom Lake Spring Cave. Observing this decline, the cave was purchased by the US Bureau of Reclamation, in cooperation with the US Fish and Wildlife Service (USFWS). They built a refugium canal and pool in 1993 (Figure 2) and constructed a wetland in Balmorhea State Park in 1996 (Edwards, 2001) to protect the populations of the Comanche Springs pupfish (*Cyprinodon elegans*) and Pecos gambusia (*Gambusia nobilis*), which are federally listed as endangered species. These fish are also present at East Sandia, Giffin, and San Solomon springs (Figure 1).

In 1999, flow ceased from the entrance of Phantom Lake Spring Cave and from May 2000 (Edwards, 2001) to the present, the US Bureau of Reclamation has pumped water from inside the cave to the refugium pool, which flows over a small dam back into the cave, to sustain the species at that location. In addition to these fish, USFWS (2012) has proposed federal endangered listing and establishing critical habitat for three aquatic invertebrates: Phantom Cave snail (*Pyrgulopsis texana*), Phantom springsnail (*Tryonia cheatumi*), and a diminutive amphipod (*Gammarus hyalleloides*). They are only known from the same four springs of the San Solomon Spring system that contain the listed species of fish.

***Figure 2.*** *Entrance of Phantom Lake Spring Cave with the edge of the refugium pool and canal in the foreground.*

## Climate Change Models, Impacts, and Water Management for the Southwestern USA

Computer programs have been created and improved, especially over the past two decades, to model the behavior of Earth's climates and predict how those climates may change under different conditions. Most models to date have focused on global climate. As computer memory and computational power has increased, the precision of the global climate models has improved and regional climate models have developed.

Widely considered the most authoritative study of global climate change, the 4th Assessment by the Inter-governmental Panel on Climate Change predicts a 3-3.5ºC mean annual increase in temperature for the southwestern USA from 1980-1999 to 2080-2099, and a 5-10% decrease in mean annual precipitation over that same period (Solomon et al., 2007). A similar in-depth and acclaimed, but more recent study focused on climate change in the USA (Karl et al., 2009). It projected slightly lower annual temperature increases for the area where San Solomon is located, 2.2-2.8 ºC, and the same annual decreases in precipitation of 5-10% by about 2090. However, those values assume low rates of emission of greenhouse gases. Their projections under a high emission rate scenario for the same area and period showed temperature increases of 5-5.5 ºC and 25-30% decreases in annual precipitation.

Many climate studies (e.g. Karl et al., 2009) have postulated several likely impacts on water resources for human and ecological use as a result of the modeled changes in climate. Those related to karst and the San Solomon area include:

- **Decreased water availability:** Increased potential for drought and diminishment and cessation of stream and spring flows, lower groundwater levels in wells and lakes, decreased rainfall and snowpack, increased water loss by evaporation, less water for use in drinking, agriculture, industry, and energy production, increased demands on water supplies for domestic, agricultural, industrial, and energy production needs, and decreased capacities for water systems to dilute pollutants.
- **Increases in water pollution:** As mean air temperature increases, surface water will become warmer, making it able to hold less dissolved oxygen which will increase the occurrence of harmful algal blooms, change the toxicity of some pollutants, increase the risk of waterborne diseases, and degrade the quality of aquatic ecosystems.
- **Changes in aquatic biology:** Aquatic species will be replaced by species better adapted to the warmer water, and temperature, rainfall, and flow changes over the next 50 years may result in the significant deterioration of the health of some aquatic ecosystems; wetlands, especially those dependent on spring flows, will be the most vulnerable.

These projected changes will require actions and alterations in water and ecosystem management that include, but are not limited to:

- **Water and ecosystem planning:** Review all existing local to regional water and ecosystem management plans, regulations, and documents related to uses that impact either water or ecosystems,

and revise them to provide sustainable water yield and habitat under the new climatic conditions.

- **Investments in water supply infrastructure:** Installation of metering gauges and low water use fixtures, fix leaks in water distribution systems, construction of water recycling and reuse facilities and pipelines.
- **Water conservation regulations and incentives:** Establish water use limits, water use allocation, tiered pricing with greater per unit costs for higher water use, community rules on when or if lawns may be watered, requirements for low-water systems on new construction, and tax incentives and rebates for converting existing equipment to low-water use systems.
- **Water pollution prevention regulations, incentives, and infrastructure:** Create or revise rules and discharge permits for maximum pollutant and nutrient loading, develop requirements for new construction to include pollution prevention and mitigation facilities, and tax incentives and rebates to provide existing construction with new or upgraded prevention and mitigation facilities.
- **Ecosystem management:** Establish or revise land use, game, and non-game regulations, recovery plans, refugia, and tax incentives and rebates for enhancing, restoring, and creating habitat, and increasing monitoring, removal of exotic species, and mitigation of other threats.

## Climate Change and the San Solomon Spring System

In many ways, the San Solomon Spring system is typical of many karst systems in the western part of the USA. While it is technically within a large karst region, the Edwards Plateau, the location of its drainage area on the fringe of the plateau make it more like many western karst regions which are small and hydrogeologically isolated. Consequently, many of the ecosystems they support are small, isolated and thus more vulnerable to impact. Such isolated desert springs are often called *cienegas* in the US southwest.

The term *cienegas* is especially used by biologists to identify springs and associated wetlands whose flow dries before reaching a perennial stream, thus isolating the aquatic populations depending on those flows to the water volume, velocity, depth, chemistry, temperature, and other conditions associated with that spring. Even during flood events, when flows may reach perennial streams, the cienega species remain within the cienega having adapted to its conditions, including food sources and predators. They often cannot survive in other aquatic systems. If the flow of the springs, or other conditions, threaten the survival of its species, they may be listed as threatened or endangered by the USFWS, as at the San Solomon Spring system.

Like many western areas with small human populations, groundwater pumping in the San Solomon area is potentially the primary reason for declining aquifer levels and associated spring and stream flows. Perhaps the best known example of a spring that ceased flowing due to over-pumping of groundwater in Texas is Comanche Spring in Fort Stockton, 85 km to the east of San Solomon Spring. One of the larger springs in Texas, Comanche Spring was the type locality for the Comanche Spring pupfish found at San Solomon (USFWS, 1980).

At the time of this writing, May 2013, the effect of climate change in the southwestern USA is not readily distinguishable from a long-term drought. NOAA (2013) shows the San Solomon area as in a “severe” drought and predicts the drought currently occurring throughout the southwestern USA will persist or intensify at least through the summer of 2013. For the time being, the decreased spring flows can be argued as the result of pumping and the drought, not climate change. However, assuming the drought or at least prolonged periods of lower than average precipitation continue, climate change will establish a new normal for average rainfall. What effect will that have on water and ecosystem management in the southern USA? One of two scenarios is likely: market-driven and ecology-driven.

Comanche Spring is a likely example of future market-driven solutions to climate change stresses. Although it is the type locality of an endangered species, the spring went dry in 1962 (Brune, 1981) and the listed fish were lost in that location several years before they were listed. Audsley (1956) observed a direct correlation between groundwater pumping and declines in spring flow, but without ecological mandates to consider, pumping continued until the springs dried (Figure 3).

No subsequent detailed hydrogeologic study for the Comanche Spring area could be located for this report, but various personal communications suggest that groundwater declines may have stabilized since the

springs dried. Pumping is believed by some to be at a rate that is sustainable for agricultural, domestic, and industrial use, but not to maintain spring flow. While groundwater levels are lower, the increased energy cost of raising the water to the surface is currently affordable for market needs. Assuming climate change results in declines in precipitation similar to the San Solomon area, and simplistically results in similar percentages of lost aquifer recharge, then the Fort Stockton community would likely be able to decrease groundwater use by 5-10% through conservation and other non-drastic measures to maintain sustainable water use under Karl et al.'s (2009) low emissions scenario by 2090. However, decreasing water use by 25-30% under the high emissions scenario would likely force market economics to determine if expensive water savings and production infrastructure will be developed or agricultural water use substantially reduced. This general scenario will probably play out across the American southwest as climate changes progresses.

The San Solomon Spring system serves as a probable example of future ecology-driven responses to the modeled climate change. While it is relatively close to Comanche Spring, there is a wide regulatory distance between the spring groups due to the Endangered Species Act of 1973. This Act provides the legal authority for the USFWS to require management of an aquifer to preserve spring flows for endangered species preservation. When that authority was questioned in the San Antonio, Texas, area, a federal judge ruled that either the state could take control of the Edwards (Balcones Fault Zone) Aquifer to protect endangered species depending on its spring flows, or the federal government would take control. This decision resulted in the state's creation of the Edwards Aquifer Authority to establish and enforce pumping limits and other means to limit excessive groundwater withdrawal (Texas Senate, 1993).

***Figure 3.*** *Presently dry Comanche Spring. The circular culvert is about 70 cm in diameter. It opens to a cave which is the source of the spring.*

Currently, declines in aquifer levels in the San Solomon area have resulted in the drying of only Phantom Lake Spring Cave, where a temporary solution has been applied by pumping water from the cave into a pool to sustain the listed fish and then letting it flow back in. No legal restrictions on water use or management have yet been applied. However, such restrictions may be imposed if conservation and other voluntary water saving methods are insufficient to keep the other springs in the San Solomon system from going dry. Yet before any major legal action can be taken, substantial hydrogeological research should be conducted first. The resulting data would serve as a foundation for assessing the areas and volumes of groundwater lost to pumping and climate change in order to accurately predict declines in aquifer levels that would threaten additional spring flows.

Anaya and Jones (2009) provided the most recent and detailed hydrogeologic study of the Edwards-Trinity Aquifer. They described how limited data compromised the precision of their model in some areas. This is especially true for the San Solomon Spring system area. Despite the presence of major springs that have been well known for decades, their model shows the aquifer in that area as dry or of an uncertain saturated thickness. As noted previously in this report, divers have explored Phantom Lake Spring Cave to a depth of 140.8 m, demonstrating a substantial saturated aquifer thickness. Other data on the area are also not available for their model, arguably making their results unreliable for the San Solomon Spring system.

The additional relevance of Anaya and Jones's (2009) study is that it is typical of the state of knowledge of many aquifers in the southwestern part of the USA. The region is sparsely populated, few wells and springs are available for monitoring and from which to construct accurate groundwater availability models, and local economic resources are often insufficient to fund the installation of multi-year monitoring networks, analysis of their data, and related appropriate hydrogeological research. The expense and complexity of such a project substantially increases when the aquifer is karstic.

Consequently, the ecology-driven response to climate change at the San Solomon system will likely be, as demonstrated in many endangered species recovery plans, for the USFWS to take action based on the best available data and address uncertainties by erring on the side of species protection. However, erring to protect the species is no assurance of adequate protection where the uncertainties are great or undefined. As spring flows continue to across the southwestern USA and climate changes threaten ecosystems around the country, USFWS will almost certainly receive increasing numbers of petitions to list additional species. Research funds may be lost to administrative costs for listing and the seemingly endless legal challenges that accompany many listings and management actions.

Regardless of whether management is driven by market or ecological forces, computer-based tools are becoming available to assist support the decision-making process. Following are two examples; neither has yet been applied to the San Solomon area.

The US Environmental Protection Agency (2013) released the BASINS climate assessment tool in 2007. This environmental analysis software package combines geographical information system and national watershed data with watershed modeling tools to facilitate watershed-based assessments of the potential implications of climate variability and change on surface water systems. It allows users to create climate change scenarios to quickly assess a wide range of potential situations on how weather and climate could affect their water resources, and guide the creation of effective management strategies.

Complimenting BASINS, ICLEI-Local Governments for Sustainability (2013) offers ADAPT (Adaptation Database and Planning Tool) as a management tool specifically for community governments. It is based on-line where users input data and evaluate their community's vulnerabilities, select preparedness goals, and create and prioritize responses.

## Conclusions

If today's climate change models prove correct, the impacts of climate change will severely tax the resourcefulness and resources of water and ecosystem managers. Karst aquifers will prove especially problematic. They are far more difficult to accurately model than other aquifers. Effective study of karst systems requires more techniques, research, and data.

Effective management of karst aquifers is often comprised by poor understanding of those systems. The general public, as well as resource managers not trained in karst water and ecosystem management, often suffer from misconceptions that underestimate adverse environmental impacts. For example, wells that discharge large volumes of water do not necessarily reflect aquifer-full conditions when they tap high-permeability conduits. Also, karst springs without rare species may not seem to reflect ecological threats if rare but unknown groundwater faunas occur within the conduits feeding those springs and are adversely impacted by climatic changes. This is seen at the San Solomon Spring system, where listed and non-listed rare species occur in surface flows, but it was only by diving into Phantom Lake Spring Cave that Krejca (2005) found three stygobites in the aquifer, one of which is likely a new species.

Market conditions can serve as an effective water management tool if ecology is not a consideration, as well as recreation and other uses of potentially lost surface flows. However, water withdrawal must be demonstrated as sustainable in perpetuity and in consideration of climatic conditions and changes.

Ecosystem preservation can be used to manage water resources for human and ecological purposes. It requires a more in-depth understanding of aquifer hydrogeology and how it affects ecosystem health. The production of water resource modeling tools should continue to grow and assist managers in their planning process, whether it is driven by market or ecosystem forces.

There is insufficient information currently available on the hydrogeology of the San Solomon Spring system to predict if additional springs, besides Phantom Lake Spring Cave, will dry or decline to unsustainably low levels for their populations of endangered species under the current climate change scenarios for that region. Additional study is certainly warranted. However, the study of water and ecosystem management at the San Solomon Spring system can serve as an example for other springs in the southwestern USA, especially those flowing from karst aquifers.

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## Biography

Dr. George Veni is the Executive Director of the National Cave and Karst Research Institute (NCKRI) and an internationally recognized hydrogeologist specializing in caves and karst terrains. Prior to NCKRI, he owned and served as principal investigator of George Veni and Associates for more than 20 years and has conducted extensive karst research throughout the United States and in several other countries. Since 2009, he has served as the Vice President of Administration for the International Union of Speleology. He has been as a committee advisor for geological, geographical, and biological dissertations and theses for three universities, taught karst geoscience courses for Western Kentucky University for 11 years, and taught karst science and management workshops internationally for NCKRI since 2011. Three cave-dwelling species have been named in his honor. He has published and presented nearly 200 papers, including four books, on hydrogeology, biology, and environmental management in karst terrains.